EVALUATION OF A CANOPY SYSTEM AND A SIMPLE CALORIMETER FOR RESTING METABOLISM USING A RESPIRATORY SIMULATOR

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Abstract-The evaluation of energy expenditure is of great importance, not only during health promotion, but also during recovery from disease. The measurement of oxygen uptake is the most reliable method for measuring energy expenditure, but, for estimating resting metabolism, there is still a need for sophisticated equipment. We have developed and evaluated a simple calorimeter and compared it with the flow-through (Canopy) system. A respiratory simulator was used to evaluate oxygen uptake at different flow rates. A known concentration of mixed gases flows into the system via the respiratory simulator and the oxygen concentrations and flow rates were compared. The results indicate that large errors in the measurement of oxygen uptake occurred at low flow rates, but these errors were about 5% under estimated values in the simple calorimeter. The measurement error at low flow rates is about 10% in the Canopy system. From these results, we concluded that the simple calorimeter can be used to measure oxygen uptake under resting conditions; however, the Canopy system would be unsuitable for measurement in a subject with small ventilation, such as an elderly patient. Great attention is needed when these oxygen measurement systems are applied to patients with very low flow rates.

Keywords - resting metabolism, calorimeter, Canopy system, oxygen uptake, flow rate

I. INTRODUCTION

The measurement of energy consumption is important in various fields, such as sports medicine, cardiovascular physiology, and the prevention of life-style related disease because it is a potential index of physical activity. There are many methods for measuring energy consumption [1-3], but measurement of oxygen (O_2) consumption is the most acceptable and reliable approach, since O_2 uptake is based on energy consumption [2].

Many investigations have measured O_2 uptake to evaluate energy consumption during work. The open-circuit system is commonly used for the measurement of O_2 uptake, and uses approaches such as the Douglas bag method, breath-by-breath, mixing chamber, and flow-through methods. The breath-by-breath method has been widely used in sports medicine for anaerobic threshold detection [4][5]. This method is best suited to exercise tests with rapid increases in workload. The mixing chamber method is based on the Douglas bag system. This device has a chamber where the gases from several exhaled breaths are mixed. The concentration of the mixed expired gas can be measured downstream from the chamber [6]. The flow-through method requires a flow of air passing around the subject's head, which may be enclosed in a Canopy [7]. The airflow and O_2 concentration on the outflow side are measured. Since the expired gas of the subject is greatly diluted, the O_2 and carbon dioxide (CO_2) concentrations must be measured precisely.

There are several methods for measuring O_2 uptake that are worthy of development, but almost all O_2 uptake monitors are used for estimating the effects of exercise and training in athletes. These subjects have relatively low resting and basal metabolisms, with low flow rates. In addition, the elderly people and patients after recovery the disease have low resting and basal metabolisms. The metrology of monitoring O_2 uptake under low flow rates must be considered in terms of accuracy and reliability. One of the possible techniques for estimating resting metabolism is the Canopy system. We have developed a simple calorimeter by applying the mixing chamber method. The aim of this study was to evaluate these two devices in vitro using a simple respiratory simulator.

II. METHODOLOGY

A. Apparatus

1) *A simple calorimeter*: The system comprises a mask, a flowmeter, an O_2 sensor, and data logging device (Metavine, Vine, Tokyo, Japan). The flowmeter and the oxygen sensor were a rotameter and a zirconia-type O_2 sensor, respectively. The rotameter has a rotor that responds to the airflow, and the flow rate is measured by the number of turns of the rotor. According to the specifications, this rotor rotates at 80 turns per 16 l/min of airflow with a resolution of 0.2 l, and the pressure drop is about 0.2 kPa (2 cmH$_2$O) at 100 l/min. The measurement error was within ±10 turns in the flow range of 5-60 l/min. The measurement error increases significantly at flow rates of less than 5 l/min, with the rotor not responding to a flow of less than 2.5 l/min. The zirconia electrolyte disc in the zirconia O_2 sensor has electrodes on both sides, and the ability to pass O_2 ions at high temperatures. When a cap with an aperture is attached to one side (cathode) of the disc, gas diffusion is limited and a saturated current is observed. The limiting current is proportional to the ambient O_2 concentration. The linearity is from 1 ppm to 95% O_2. Neither a reference gas nor recalibration is required. The functional life of the sensor is more than three years in air. The system is based on a mixing chamber method, but any special chamber can be used. The flow rate and O_2 concentration are measured continuously, and the data are averaged and stored every minute.

2) *A canopy system*: The canopy system (Vmax29, SensorMedics, CA) is based on a flow-through method. The airflow rate through the flow-through circuit must be higher than the peak inspiratory and expiratory flow rates; otherwise, backflow may occur in the circuit and cause rebreathing. The expired gas and room air should be well mixed to eliminate phasic change in gas concentration because of respiration,

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Abstract

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and so two mixing chambers are used. The mixed gas is sampled and gas contents are measured using a paramagnetic O_2 sensor and non-dispersive infrared analyzer for CO_2. The accuracy of the paramagnetic O_2 sensor was ± 0.02% O_2, resolution was ± 0.01% O_2. Airflow was measured by a hot-wire anemometer which consists of a fine metal wire heated by an electric current. The airflow velocity is estimated by the amount of heat transferred from the wire to the gas and the temperature difference between the wire and gas temperature. Instantaneous flow range was 0-16 l/s, integrated volume range was 0-350 l/min. Flow path resistance was greater than 1.5 cmH$_2$O at 12 l/s, and accuracy was ±3% of the reading or 0.25 l/s, whichever is greater (0.2-12 l/s). The flow rate and O_2 concentration are measured continuously, and the data are averaged and stored every minute.

B. Experiment

A simple respiratory simulator, shown in Fig. 1, consists of a disc and a cylinder pump, the stroke of which can be adjusted to produce different respiratory rates. The experimental conditions are shown Table 1. We pre-determined the cylinder volume at 0.259, 0.487, or 0.974 l, and the number of rotations at 10, 15, or 20 cycles per minute. A small cylinder volume and a low number of rotations simulated hypopnoea, whereas a small cylinder volume and high number of rotations simulated hyperpnoea. In this way, nine different flow rates were assigned. The gas concentrations were pre-determined and were 15.85-15.98% O_2 and 3.91-3.94% CO_2. The ambient temperature, relative humidity, and barometric pressure were 23°C, 62%, and 1013.7 hPa (760.5 mmHg) when the simple calorimeter was evaluated, and 20°C, 30%, 1011.7 hPa (759 mmHg) when the Canopy system was evaluated. The schematic diagram of the experimental set-up is shown in Fig. 2. The Douglas bag was used to collect the gas of known concentration. The Douglas bag is connected to the calorimeter or the analyzer of the Canopy system using a one-way valve. The one-way valve was also connected to the respiratory simulator that determines flow rates. The Canopy system is shown in Fig. 3. The standard gas, whose concentration was pre-determined, passed through a dummy head in the Canopy. The mixed gas with room air and standard gas in the canopy was drawn by a pump, sampled and measured in the analyzer. The gas was allowed to flow for 30 s before the measurement started, to accommodate the dead space of the experimental system. The measurements were performed over five minutes, and the data were obtained at one-minute intervals. Ambient temperature and relative humidity were measured by a psychrometer (SK-RHG, Sato Keiryoki Mfg, Tokyo, Japan), and the barometric pressure was measured by a barometer (4610-20, Sato Keiryoki Mfg, Tokyo, Japan). The measurements obtained from the calorimeter and Canopy systems are shown in Table 2.

C. Evaluation

The standard gas condition applied in this experiment was under the ambient temperature and barometric pressure, and dry (ATPD). However, when the calorimeter calculated O_2 uptake, the expired gas was assumed to be of ambient

Fig.1 A simple respiratory simulator.

Fig.2 The schematic diagram of experimental set-up.

Fig.3 The Canopy system. The standard gas through the dummy head is mixed with the room air in the Canopy. The mixed gas flow and O_2 concentration on the outflow side (mixed standard gas with the room air) was measured by the analyzer.

Table 1. Experimental conditions.

Cylinder volume [l]	Estimated flow rate [l/min, ATPD]		
	Number of rotations [/min]		
	10	15	20
0.259	2.590	3.885	5.180
0.487	4.870	7.305	9.740
0.974	9.740	14.610	19.480

Table 2. Items of measurement by the devices. $F_{E}O_2$ and $F_{I}O_2$ are expired and inspired O_2 gas fraction, $F_{E}CO_2$ and $F_{I}CO_2$ are expired and inspired CO_2 gas fraction. P_B is the barometric pressure, and T is ambient temperature.

devices	items
calorimeter	V_E, $F_{E}O_2$
Canopy system	V_E, $F_{E}O_2$, $F_{E}CO_2$, $F_{I}O_2$, $F_{I}CO_2$, P_B, T

temperature and barometric pressure, and fully saturated with water vapor (ATPS). Similarly, the Canopy system assumed the expired gas to be of normal body temperature, pressure and fully saturated with water vapor (BTPS). Thus, flow rates were recalculated into standard temperature and pressure (273 K, 101.325 kPa), and dry (STPD). The standard equations to measurement values of O_2 uptake were changed as follows. The equation used for the simple calorimeter was

$$\dot{V}_{O_2M}\ STPD = FR_M ATPS \times \left(0.207 + F_{EO_2M} \right) \times 0.89$$

The equation was changed to

$$\dot{V}_{O_2M}\ STPD = FR_M STPD \times \left(0.207 - F_{EO_2M} \right)$$

where, $\dot{V}_{O_2M}\ STPD$ is measured O_2 uptake, FR_M is measured flow rate. O_2 concentration of room air was fixed at 20.7% for the calorimeter. Similarly, the equation used for the Canopy system is

$$\dot{V}_{O_2M}\ STPD = FR_M BTPS$$
$$\times \left(\frac{F_{IO_2M}\left(1 - F_{EO_2M} - F_{ECO_2M}\right)}{F_{IO_2M} - F_{ICO_2M}} - F_{EO_2M} \right)$$
$$\times \left(\frac{273 \times (PB - 47)}{310 \times 760} \right)$$

It was changed to

$$\dot{V}_{O_2M}\ STPD = FR_M STPD$$
$$\times \left(\frac{F_{IO_2M}\left(1 - F_{EO_2M} - F_{ECO_2M}\right)}{\left(1 - F_{IO_2M} - F_{ICO_2M}\right)} - F_{EO_2M} \right)$$

where F_{EO_2M} and F_{IO_2M} are the measured expired and inspired O_2 gas fractions, F_{ECO_2M} and F_{ICO_2M} are the measured expired and inspired CO_2 gas fractions. PB is the barometric pressure.

When the O_2 concentration of the room air is 20.9% [8], the estimated value of O_2 uptake ($\dot{V}_{O_2E}\ STPD$) was calculated as

$$\dot{V}_{O_2E}\ STPD = FR_E STPD \times \left(0.209 - F_{EO_2E} \right)$$

where, $FR_E STPD$ is the estimated flow rate, and F_{EO_2E} is the estimated expired O_2 gas fraction.

The flow rate, O_2 concentration, and O_2 uptake were compared with the estimated values. The measurement error was defined as

$$Error[\%] = 100 \times \left(\frac{measured\,value - estimated\,value}{estimated\,value} \right)$$
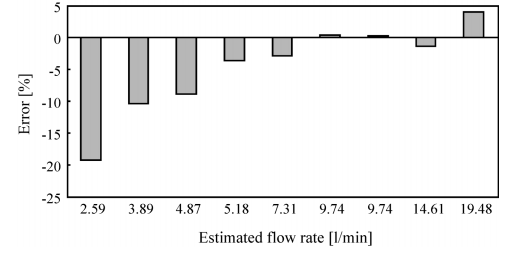
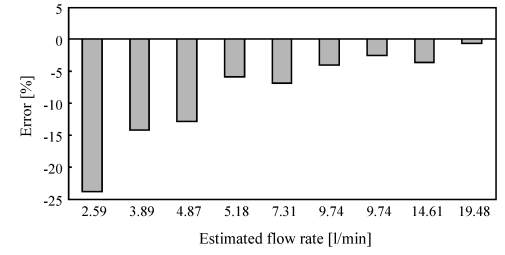Fig.4. Evaluation of flow rate at different flow volumes (calorimeter).

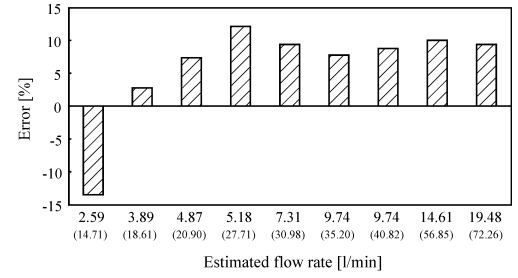Fig.5. Evaluation of O_2 uptake at different flow rate (calorimeter).

Fig.6. Evaluation of O_2 uptake at measured flow rate (Canopy system). Measured flow rates [l/min] were shown in parentheses.

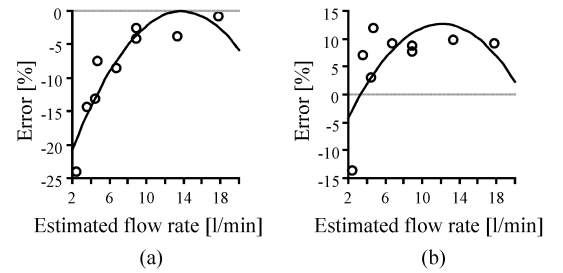(a)   (b)

Fig.7. The errors in O_2 uptake at the calorimeter (a) and the Canopy system (b). Regression equations for the error as function of estimated flow rate were: for the calorimeter, Error = -28.44 + 4.412FR_E - 0.149FR_E^2 (R^2 = 0.851); for the Canopy system, Error = -11.523 + 4.017FR_E - 0.166FR_E^2 (R^2 = 0.467).

III. RESULTS

A. The simple calorimeter

The flow rate and O_2 uptake under nine different sets of experimental conditions were calculated, and the errors are shown in Figs 3 and 4. Under the condition of lower flow rates, flow rate and O_2 uptakes show higher errors. The maximum error was observed at an estimated flow rate of 2.59 l/min. However, the errors in O_2 concentration were less than 1% throughout the whole measurement range. When

comparing the number of rotations with the cylinder volume, a small cylinder volume of 0.259 l gave a larger error ($P < 0.01$), and the error in O_2 uptake was smaller when the number of rotations was large ($P < 0.01$). According to the number of rotations, the error in O_2 uptake was smaller with a larger cylinder volume ($P < 0.01$).

B. The Canopy system

When O_2 uptake was measured by the Canopy system, the estimated values of O_2 concentration and flow rate at the analyzer were unclear; thus, only O_2 uptake was evaluated. The errors in O_2 uptake are shown in Fig. 6. The estimated flow rate of 2.59 l/min gave a negative error. A small cylinder volume of 0.259 l gave a larger error in O_2 uptake ($P < 0.01$) when the number of rotations was 10. Even if the cylinder volume was 0.259 l, the error in O_2 uptake was smaller when the number of rotations was large ($P < 0.01$).

IV. DISCUSSION

The simple calorimeter was developed for the estimation of resting metabolism based on the measurement of O_2 uptake. The greatest error occurred at the lower flow rates (Fig. 7(a)), and smaller cylinder volumes. This phenomenon originated in the specifications of the rotameter. Because the rotameter has moving parts with mechanical inertia, it cannot respond to a rapid change in airflow at low flow volumes. The measurement error in this type of rotameter increases significantly at flow rates of less than 5 l/min, and the rotor does not respond at all to a flow of less than 2.5 l/min. Accordingly, large errors in O_2 uptake of over 10% were observed at an estimated flow rate of less than 5 l/min. These results indicate that the developed calorimeter is not reliable for measurement in a subject with ventilation of less than 5 l/min. Resting ventilation in an adult, however, is about 6.0 l/min (BTPS) [9] and, even an elderly patient, in our experience, respires at about 5.0-7.0 l/min. Therefore, the developed calorimeter can be used to measure O_2 uptake in the resting condition.

The Canopy system was constructed for the measurement of resting metabolism. The errors were consistently about 10% when estimated flow rates were more than 4.87 l/min. The mixed airflow must be constant in the flow-through system. The flow rate measured by the flowmeter was larger than the set-up flow rate. The accuracy of the hot-wire anemometer was poor at low flow rates and the device was not reliable under our experimental conditions. In addition, the flow distribution of the Canopy must be considered. The flow is laminar at a low flow rate and thus the assumption of the Canopy system producing well-mixed gases could not be applied in this situation. In measuring elderly patients, the drained gas would be 15-17 l/min under our previous experimental conditions. When these flow rates, Reynolds number were 970-1099. The measurement error of the Canopy system, at this flow range, is large and it would therefore be unsuitable for measurement in a subject with small ventilation such as an elderly patient.

Furthermore, the error originated in the equations for the estimate of O_2 uptake. The value of F_{IO_2} was fixed at 20.7%, and 0.89 was used as the coefficient for exchange from BTPS to STPD in the equation of the calorimeter. On the other hand,

in the Canopy system, the ventilation was calculated to flow rate measured by flowmeter, the barometric pressure, 50% relative humidity and ambient temperature. However, ambient temperature measured by this system was different from that obtained by the psychrometer. Attention must be paid to errors such as those originating in such calculations.

When we applied the O_2 uptake device to humans, the use of a mask produced further problems. The subject sometimes became hyperpnoea, and any leak in the airflow with an unfixed mask gave a lower estimate of O_2 consumption. Although, these problems are also associated with the Canopy system, the Canopy is more comfortable to wear. Consequently, there are several problems involved with the use of O_2 uptake devices for very low flow rates, and there is a need to further develop the O_2 uptake devices, especially flowmeters, for very low flow rates.

V. CONCLUSION

We have presented the results of an evaluation of a system to measure oxygen uptake, which used a respiratory simulator to evaluate oxygen uptake at nine flow rates. In the calorimeter, large errors occurred at flow rates of less than 5 l/min; however, under normal conditions, the error was about 5%. On the other hand, in a Canopy system, the error under normal conditions was large. Furthermore, the measurement error of the flowmeter in the Canopy system was large under normal conditions and flow range. Thus, the calorimeter is more reliable and accurate for the measurement of resting metabolism, although great attention is still necessary.

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